

Polarized Deep Inelastic Scattering

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Spin2002 Workshop
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Hyperfine splitting in Hydrogen

$$\Delta\nu_{\text{exp}} = 1420405751.7667(10) \text{ Hz}$$

$$\Delta\nu_{TH} = \Delta\nu_F (1 + \delta_{QED} + \delta_P)$$

↑ ↑
Fermi QED corr.

$$\delta_P = \delta_P(\text{rigid}) + \delta_P(\text{pol}) = -34.6(9) \cdot 10^{-6} + \delta_P(\text{pol})$$

where

$$\delta_P(\text{pol}) = \frac{\alpha}{\pi} \frac{m_e}{M} \frac{1}{2(1+\mu)} \int_0^\infty \frac{dq^2}{q^2} [\Delta_1(q^2) + \Delta_2(q^2)]$$

$$\Delta_1(q^2)\!=\!\frac{9}{4}\!\left[F_2(q^2)\right]^2\!+\!5M^3\int\limits_{\textsf{v}_I(q^2)}^\infty \frac{d\textsf{v}}{\textsf{v}}\beta_1(\frac{\textsf{v}^2}{q^2})G_1(\textsf{v},q^2)$$

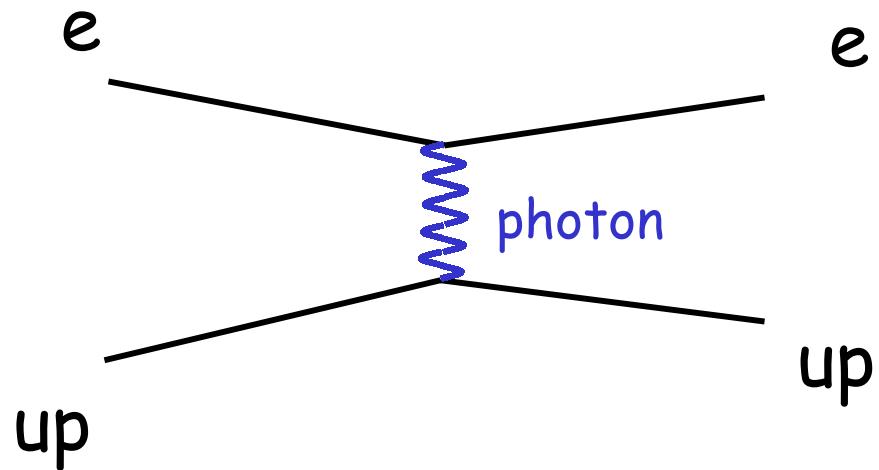
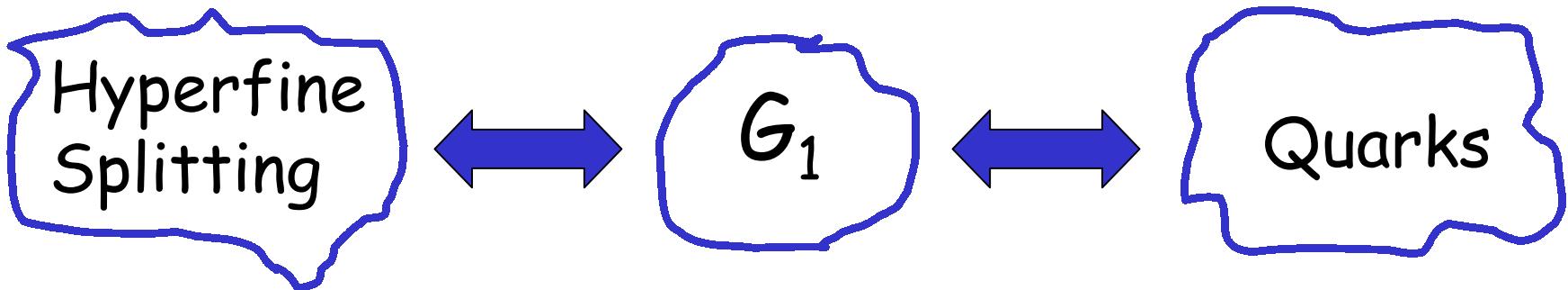
$$\Delta_2(q^2)=3M^3\int\limits_{\textsf{v}_I(q^2)}^\infty \frac{d\textsf{v}}{\textsf{v}^2}\beta_2(\frac{\textsf{v}^2}{q^2})q^2G_2(\textsf{v},q^2)$$

$$\beta_1(x) = \frac{4}{5}\Bigl(-3x + 2x^2 + 2(2-x)\sqrt{x(1+x)}\Bigr)$$

$$\beta_2(x) = 4x\Bigl(1+2x - 2\sqrt{x(1+x)}\Bigr)$$

$$F_2(q^2) = \text{Pauli Form Factor} \hspace{2cm} F_2(0) = \mu$$

$$\textsf{v}_T(q^2)=m_\pi+\frac{(m_\pi^2-q^2)}{3M}$$

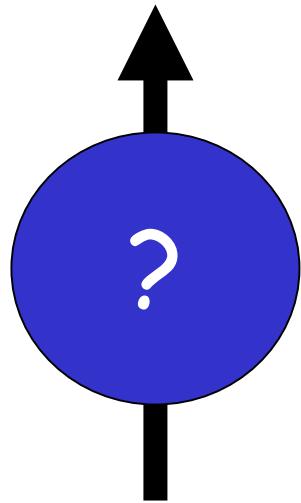


$$g_1 = \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s$$

SLAC



What carries the spin of the proton?

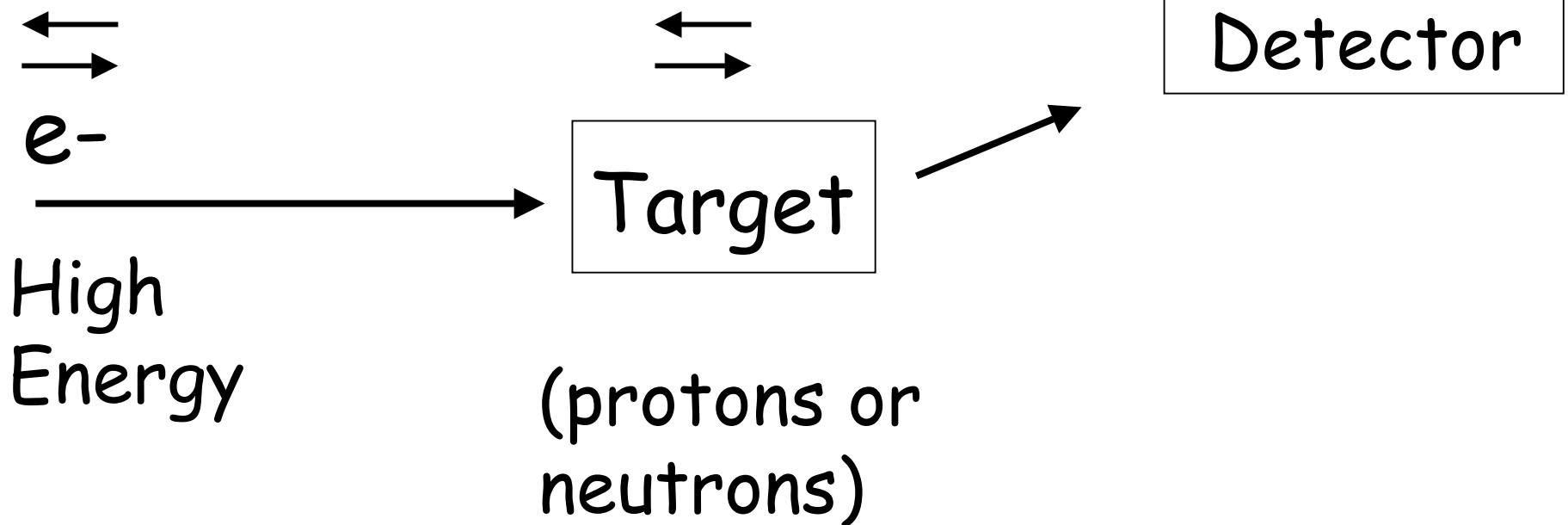


$$S = \frac{1}{2}$$

$S =$ “quarks” + “gluons”

↑
small

Polarized Deep Inelastic Scattering Experiments



Measure asymmetry

$$A(x, Q^2) = \frac{N_{\uparrow\downarrow} - N_{\uparrow\uparrow}}{N_{\uparrow\downarrow} + N_{\uparrow\uparrow}}$$

Proton (or Neutron) Spin Structure Function

$$g_1(x, Q^2) = A(x, Q^2) \cdot F_1(x, Q^2)$$



unpolarized
structure function

QCD Sum Rule

$$\int_0^1 g_1^p(x)dx - \int_0^1 g_1^n(x)dx = \frac{1}{6} \frac{g_A}{g_V}$$

Bjorken (1966)

Quark Parton Model Sum Rule

$$\int_0^1 g_1^p(x)dx = \frac{1}{18}(9F - D) \approx 0.17$$

proton

Ellis-Jaffe (1974)

$$\int_0^1 g_1^n(x)dx = \frac{1}{18}(6F - 4D) \approx -0.02$$

neutron

$g_1(x, Q^2)$

Spin Structure Function

$G_1(v, Q^2)$

Same thing!
old fashion notation

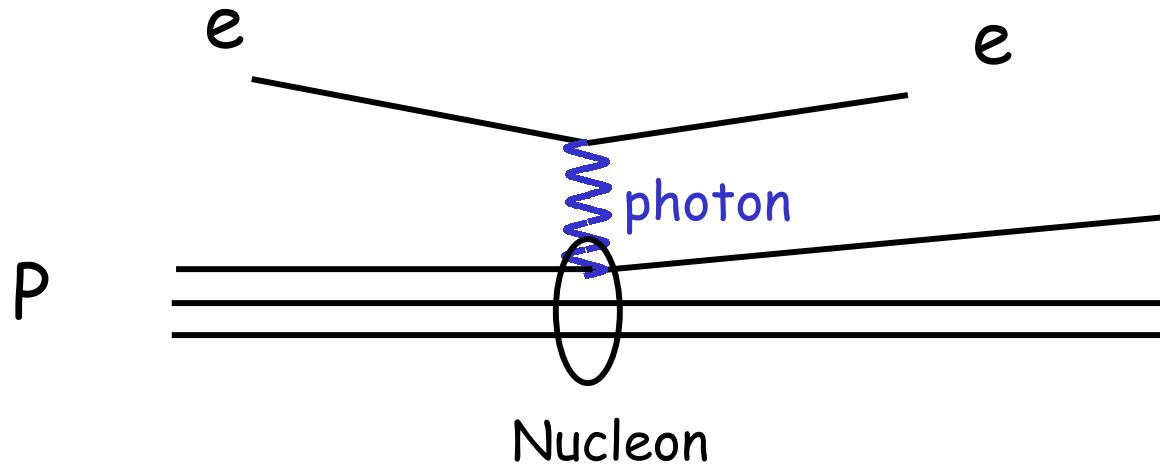
$G(x, Q^2)$

gluon distribution
(American)

$g(x, Q^2)$

gluon distribution
(European)

Deep Inelastic Lepton-Nucleon Scattering



Q^2

Four-momentum of the virtual photon

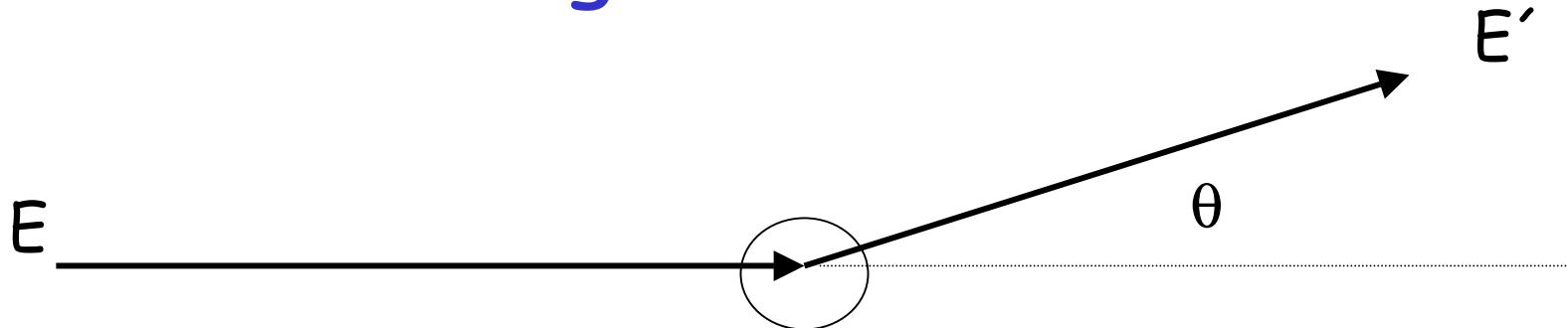
$$Q^2 \propto 1/\lambda^2$$

χ

Fraction of nucleon momentum carried by the struck quark

$$0 \leq \chi \leq 1$$

Scattering Kinematics

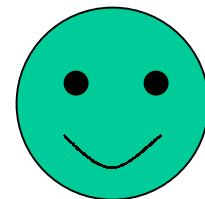


Transform 3 variables

$$\begin{matrix} E \\ E' \\ \theta \end{matrix} \quad \xrightarrow{\hspace{1cm}} \quad \begin{matrix} x \\ v \\ Q^2 \end{matrix}$$

Virtual photon energy transfer

$$\nu = E - E'$$

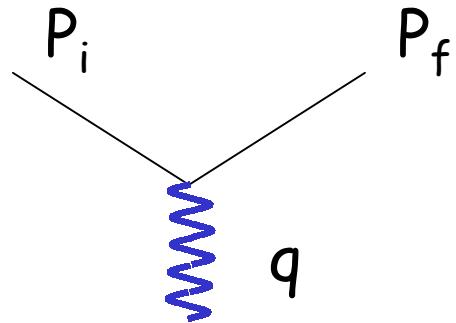


Virtual Photon 4-momentum

$$P_i - P_f = q$$

square 4-momentum

$$P_i^2 + P_f^2 - 2P_i P_f = q^2$$



Ignore electron mass, $m_e^2 \ll q^2$

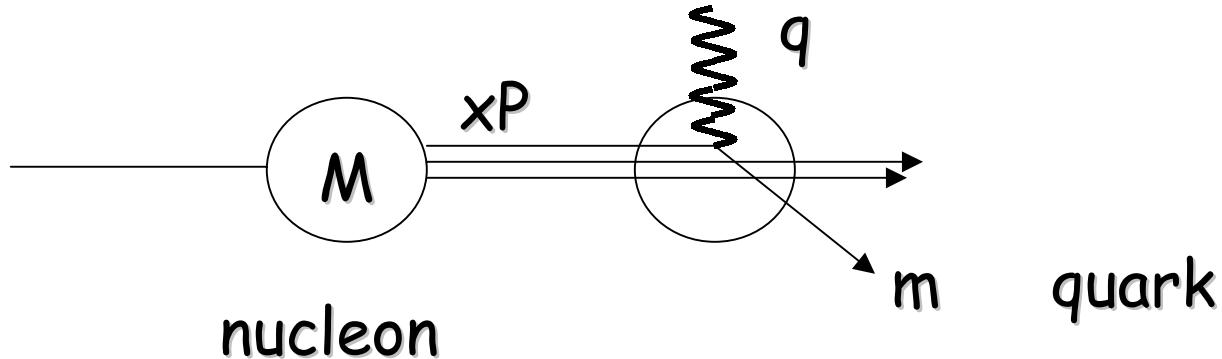
$$2EE' - 2EE'\cos\theta = -q^2 = Q^2$$

But $\sin\frac{\theta}{2} = \sqrt{\frac{1 - \cos\theta}{2}}$



$$Q^2 = 4EE' \sin^2 \frac{\theta}{2}$$

Bjorken x



$$(xP + q)^2 = -m^2 \quad \longrightarrow \quad x^2 P^2 + 2xPq + q^2 = -m^2$$

For large q^2 : $q^2 \gg m^2$ and $q^2 \gg x^2 P^2$

$$\longrightarrow 2xP \cdot q + q^2 = 0$$

In the lab frame $\longrightarrow 2xM(E - E') = -q^2$ or

$$x = \frac{Q^2}{2Mv}$$

Elastic Scattering of quark $q^2 = 2mv$

Then $x = \frac{m}{M}$

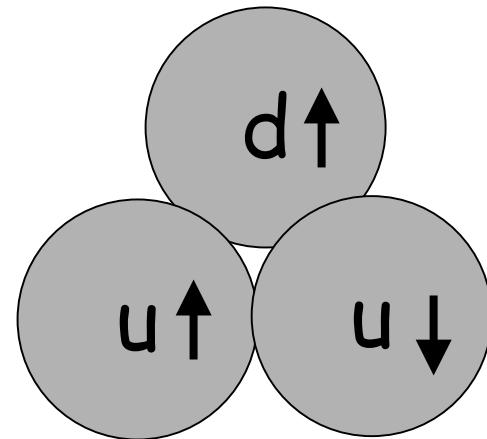
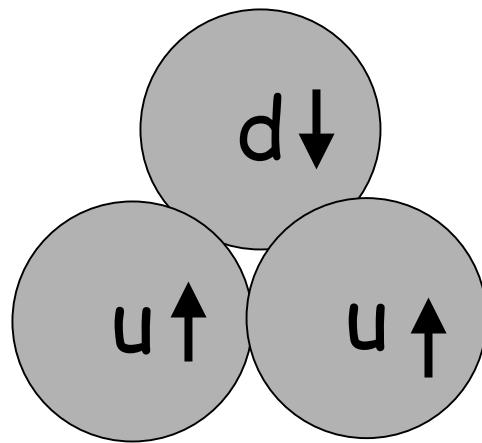
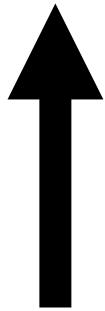
Fraction nucleon mass carried by struck quark!!!

Proton Wave function

$$\begin{aligned} |p^{\uparrow}\rangle = & \left[2|u^{\uparrow}u^{\uparrow}d^{\downarrow}\rangle + 2|u^{\uparrow}d^{\downarrow}u^{\uparrow}\rangle + 2|d^{\downarrow}u^{\uparrow}u^{\uparrow}\rangle \right. \\ & + |u^{\uparrow}u^{\downarrow}d^{\uparrow}\rangle + |u^{\uparrow}d^{\uparrow}u^{\downarrow}\rangle + |d^{\uparrow}u^{\uparrow}u^{\downarrow}\rangle \\ & \left. + |u^{\downarrow}u^{\uparrow}d^{\uparrow}\rangle + |u^{\downarrow}d^{\uparrow}u^{\uparrow}\rangle + |d^{\uparrow}u^{\downarrow}u^{\uparrow}\rangle \right] \end{aligned}$$

Square it.....

Proton and Spin



$$\frac{2}{3}$$

$$\frac{1}{3}$$

$$P(u^\uparrow) = \frac{2}{3} \cdot \frac{2}{3} + \frac{1}{3} \cdot \frac{1}{3}$$

$\stackrel{\uparrow}{u}$ quark %

left picture

$\stackrel{\uparrow}{u}$ quark %

right picture

$$P(u^\uparrow) = 5/9$$

$$P(d^\uparrow) = 1/9$$

$$P(u^\downarrow) = 1/9$$

$$P(d^\downarrow) = 2/9$$

Asymmetry Relation to Quarks

$$A^P = \frac{q_u^2 [P(u^\uparrow) - P(u^\downarrow)] + q_d^2 [P(d^\uparrow) - P(d^\downarrow)]}{q_u^2 [P(u^\uparrow) + P(u^\downarrow)] + q_d^2 [P(d^\uparrow) + P(d^\downarrow)]}$$

Plug in values....

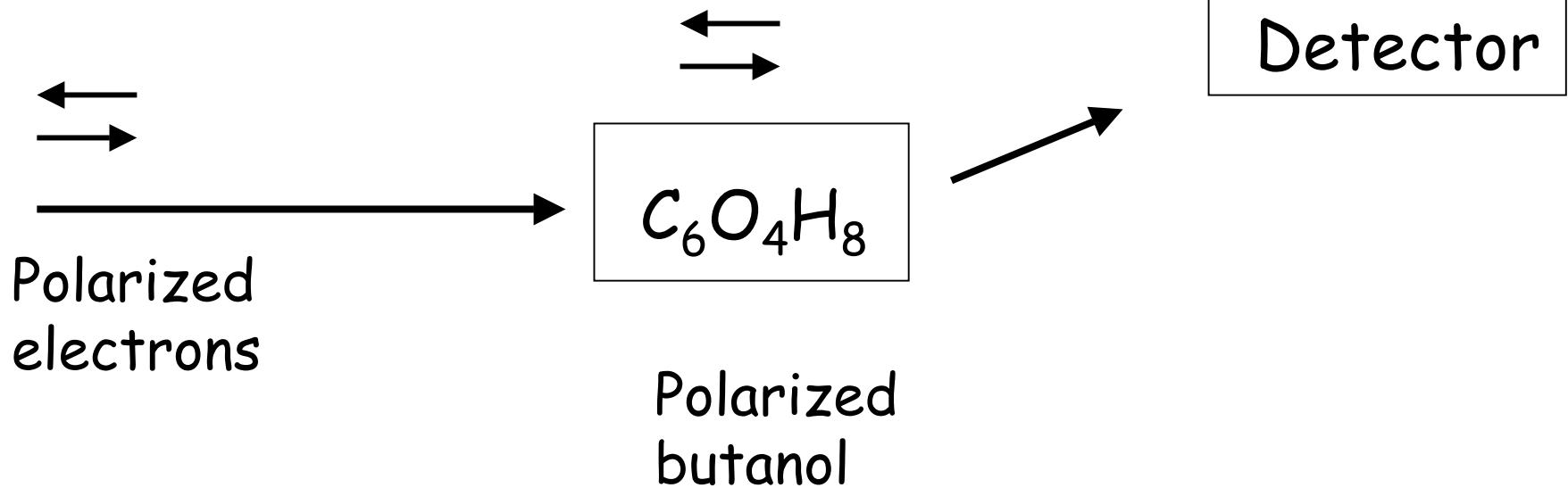
$$A^p = \frac{5}{9}$$

Neutron (interchange u and d quarks)

$$A^n = 0$$

Early SLAC Experiments

1970s and
early 1980s



Proton Spin Structure Function

A_P large

SLAC E80

Deep Inelastic Scattering of Polarized Electrons by Polarized Protons*

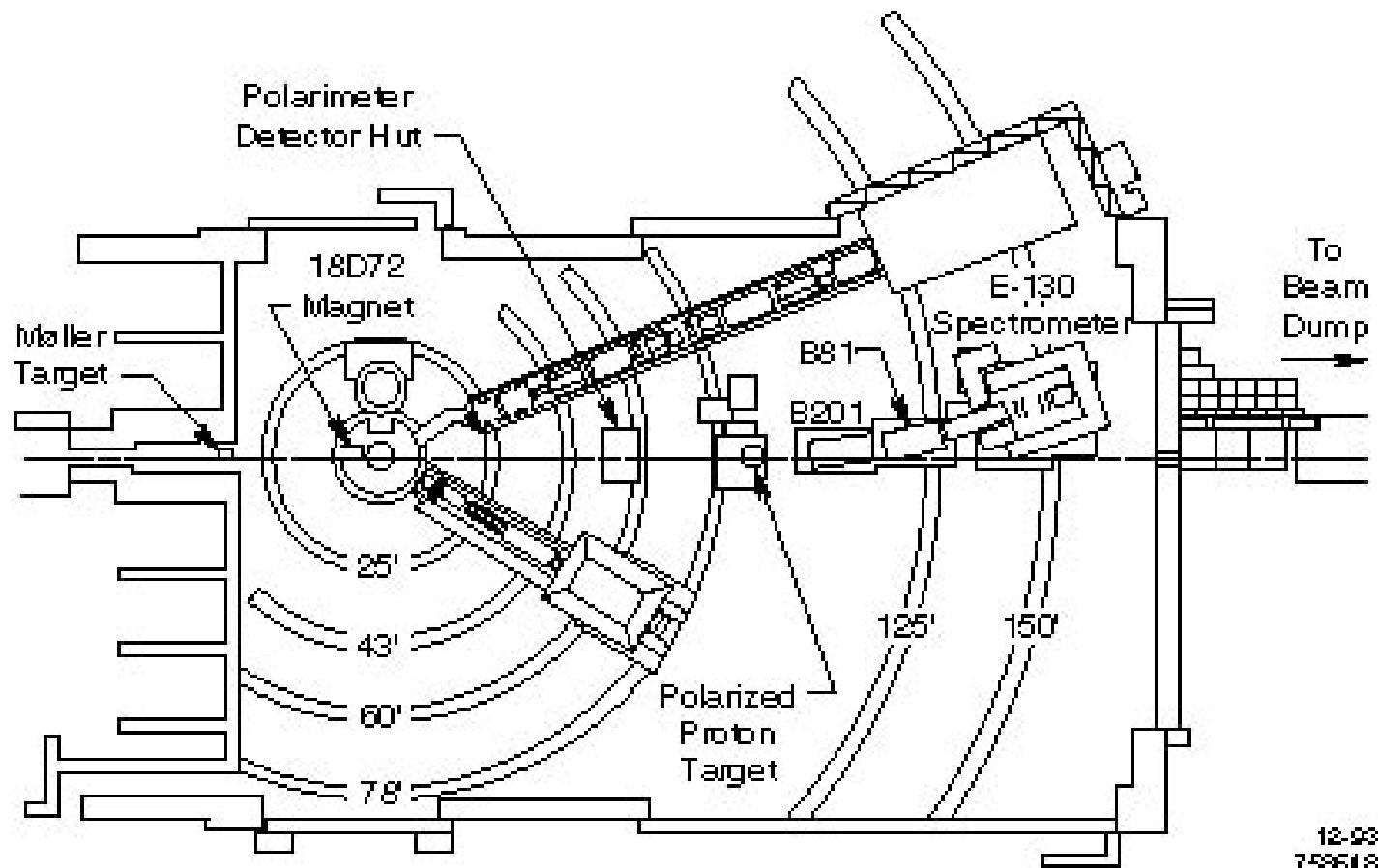
M. J. Alguard, W. W. Ash, G. Baum, J. E. Clendenin, P. S. Cooper, D. H. Coward, R. D. Ehrlich,
A. Etkin, V. W. Hughes, H. Kobayakawa, K. Kondo, M. S. Lubell, R. H. Miller, D. A. Palmer,
W. Raith, N. Sasao, K. P. Schüler, D. J. Sherden, C. K. Sinclair, and P. A. Souder

*University of Bielefeld, Bielefeld, West Germany, and City University of New York, New York, New York 10031,
and Nagoya University, Nagoya, Japan, and Stanford Linear Accelerator Center, Stanford, California 94305,
and University of Tsukuba, Ibaraki, Japan, and Yale University, New Haven, Connecticut 06520*

(Received 5 August 1976)

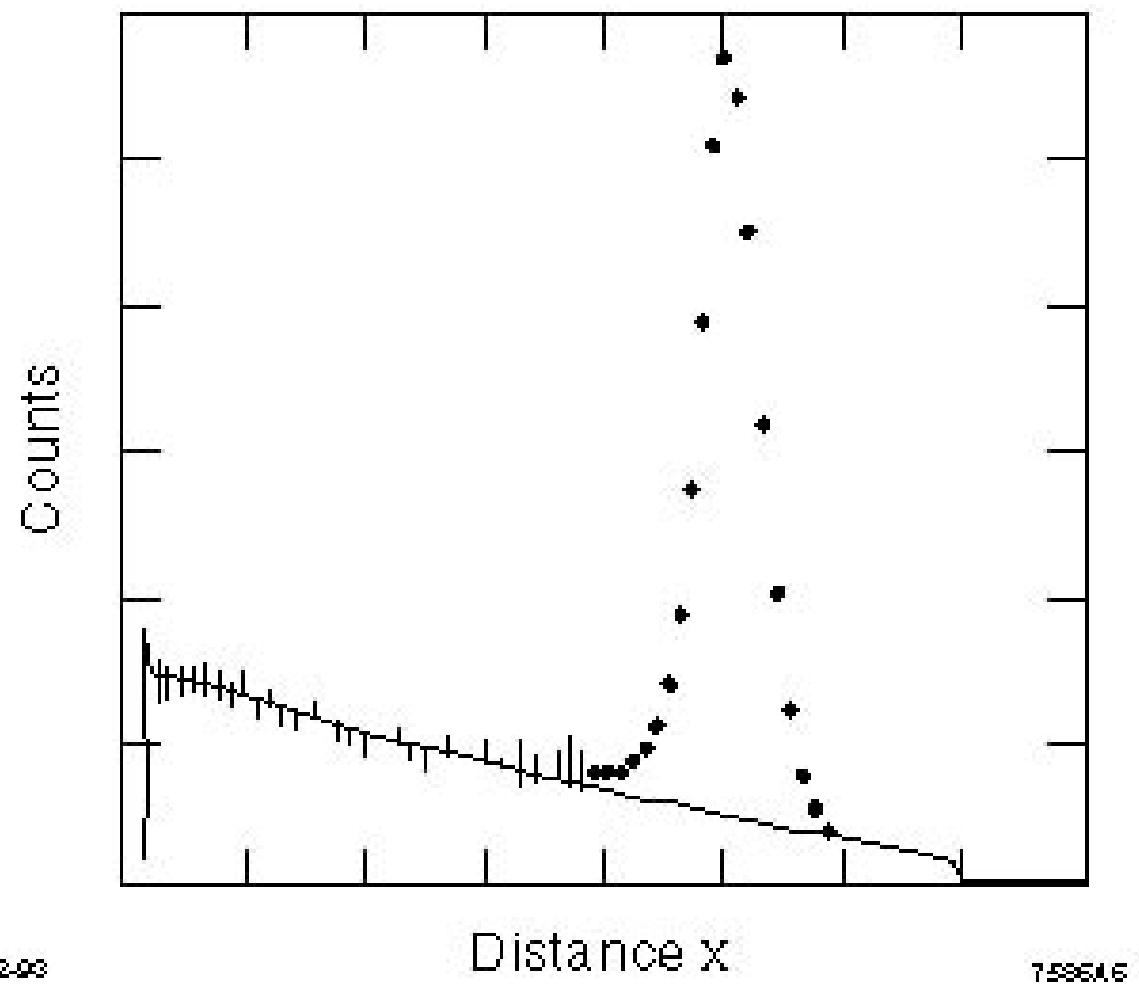
We report measurements of the asymmetry in deep inelastic scattering of longitudinally polarized electrons by longitudinally polarized protons. The antiparallel-parallel asymmetries are positive and large in agreement with predictions of quark-parton models of the proton. A limit is obtained on parity nonconservation in the scattering of longitudinally polarized electrons by unpolarized nucleons.

SLAC E80/E130 Experiments

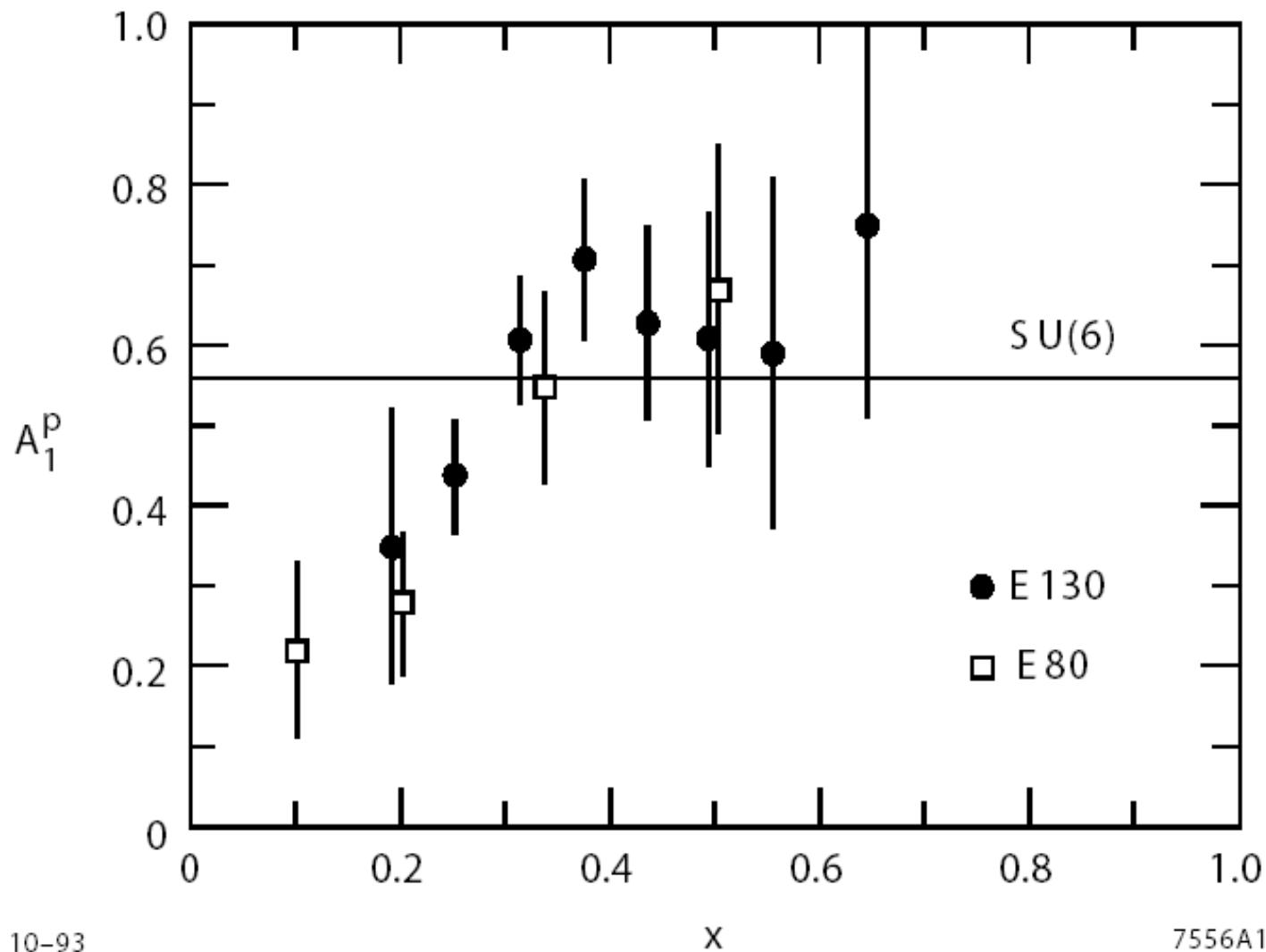


SLAC E80 Moller Polarimeter Signal

Polarized electron - polarized electron scattering

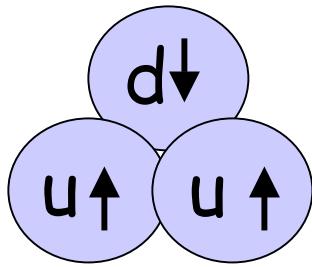


Early SLAC Experiments

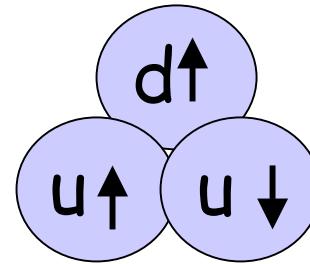


Proton

Magnetic Moments



$\frac{2}{3}$



$\frac{1}{3}$

$$\mu_{proton} = \frac{2}{3}(2\mu_{up} - \mu_{down}) + \frac{1}{3}\mu_{down}$$

$$\mu_{proton} = 3\{ \}$$

Neutron

(interchange up and down)

$$\mu_{neutron} = -2\{ \}$$

Quark Parton Model:

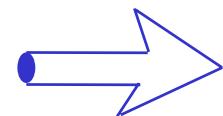
$$\frac{\mu_{proton}}{\mu_{neutron}} = -\frac{3}{2}$$

Measurements

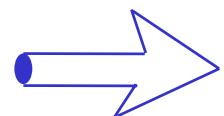
$$\mu_{proton} = 2.7\mu_N$$

$$\mu_{neutron} = -1.9\mu_N$$

SON OF E130



Neutron spin structure function



Test of the Bjorken sum rule

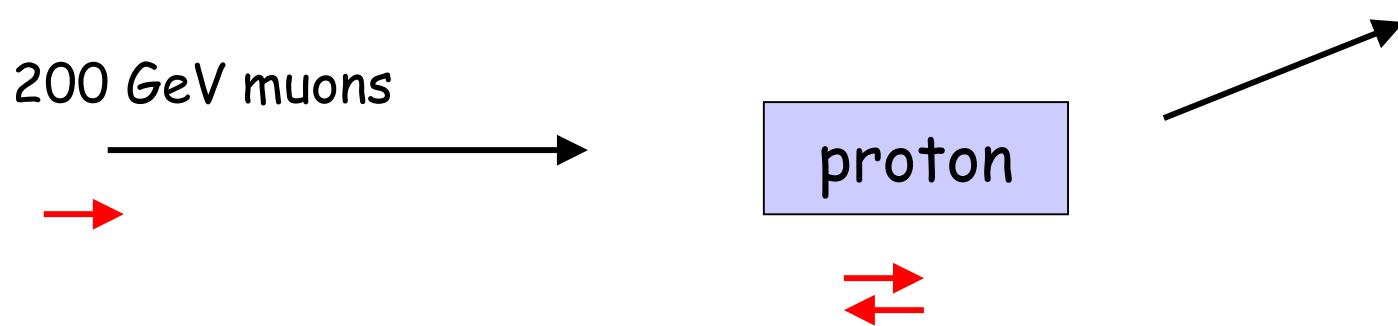


SLC vs. Fixed Target Negotiations

(1987)

15 Years ago

CERN Experiment



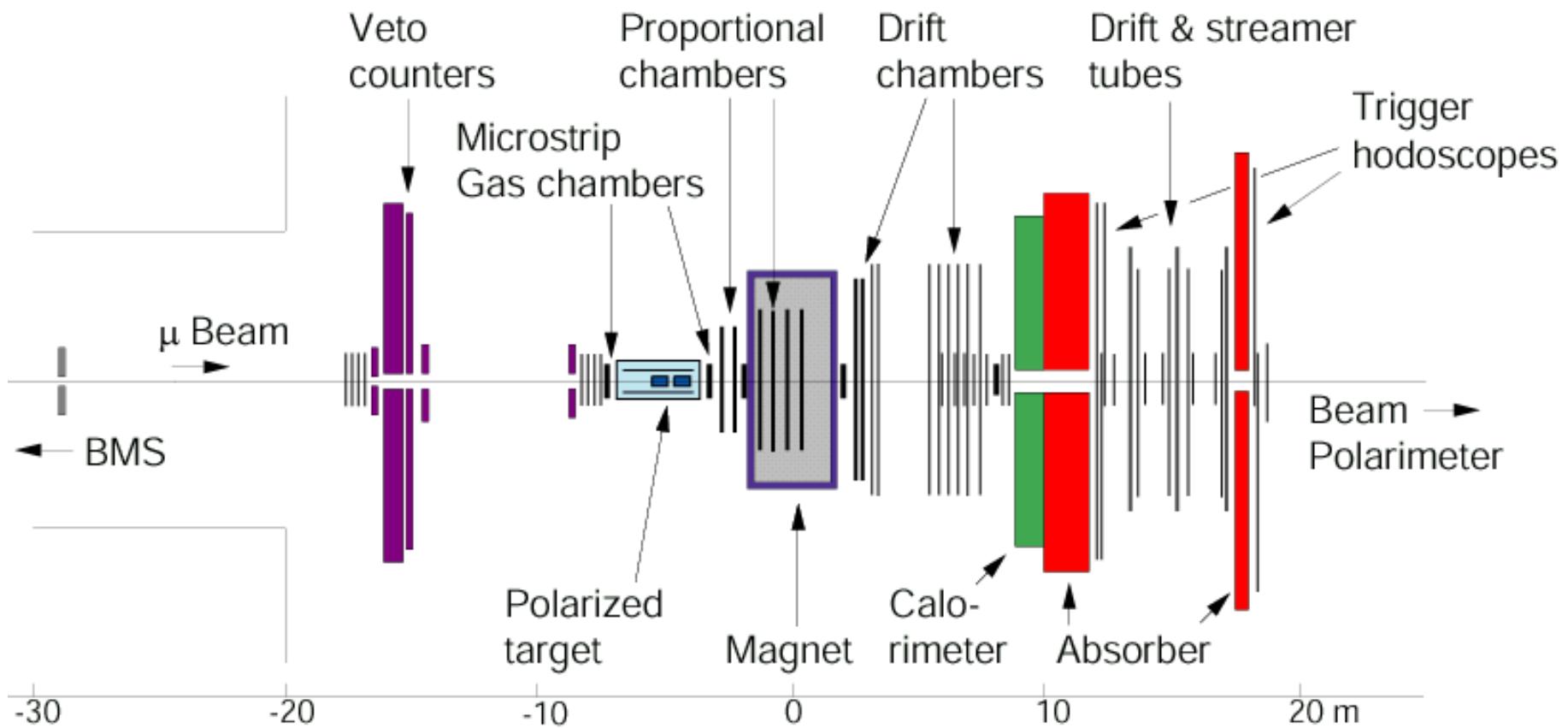
Fraction of proton spin carried by quarks

$$12\% \pm 16\%$$

Quarks do not carry proton's spin!

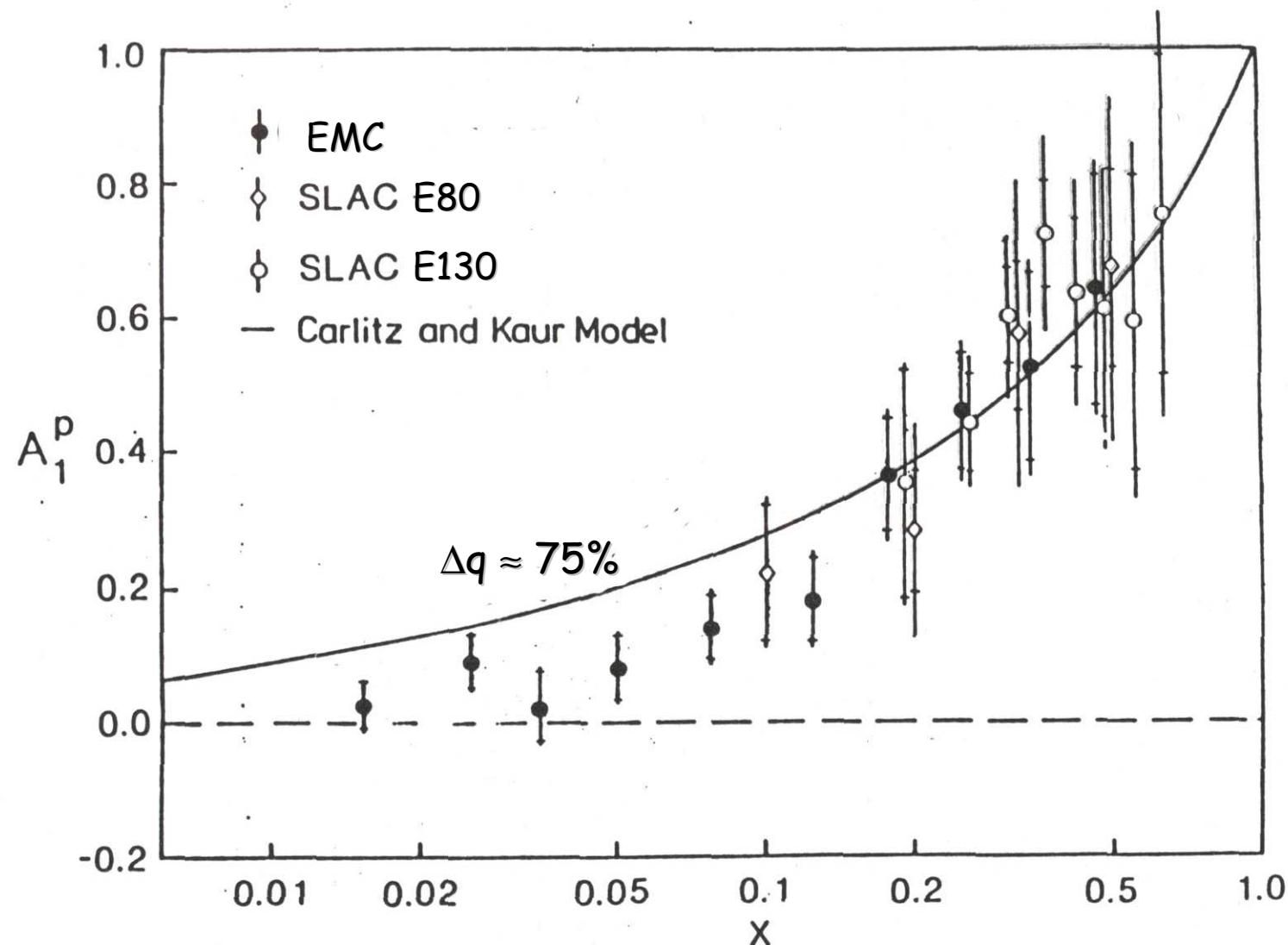
Proton Spin Crisis

EMC Experiment



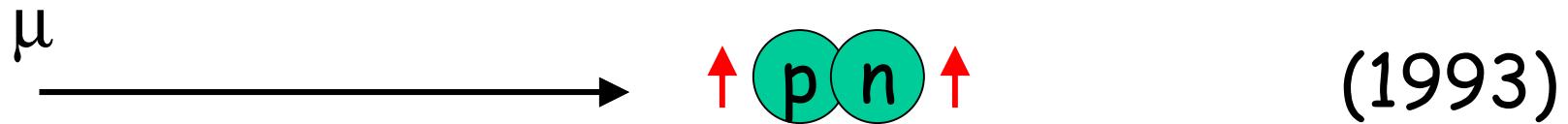
Birth of the "Proton Spin Crisis"

1988

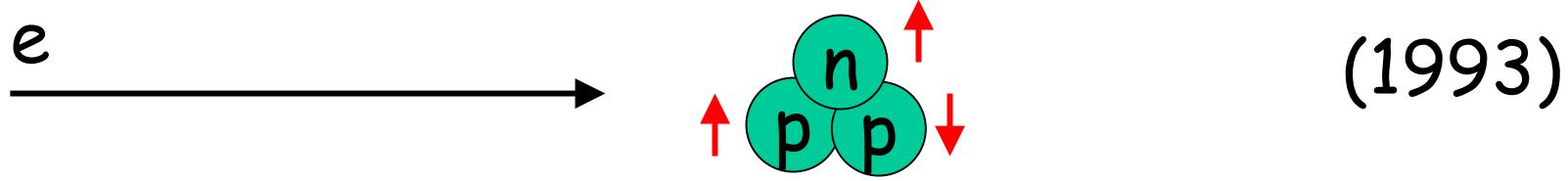


Race for the Neutron

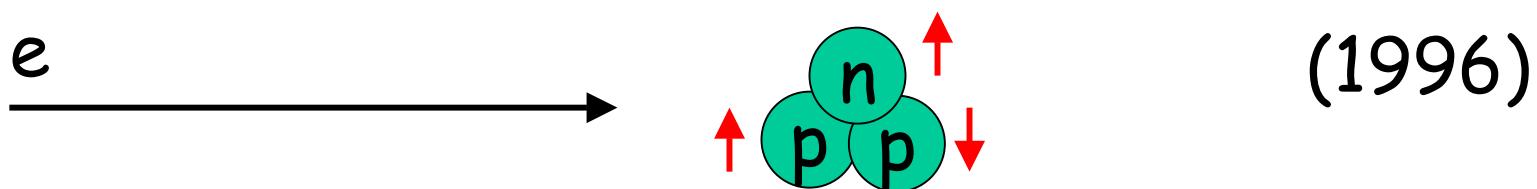
CERN SMC



SLAC E142



DESY HERMES

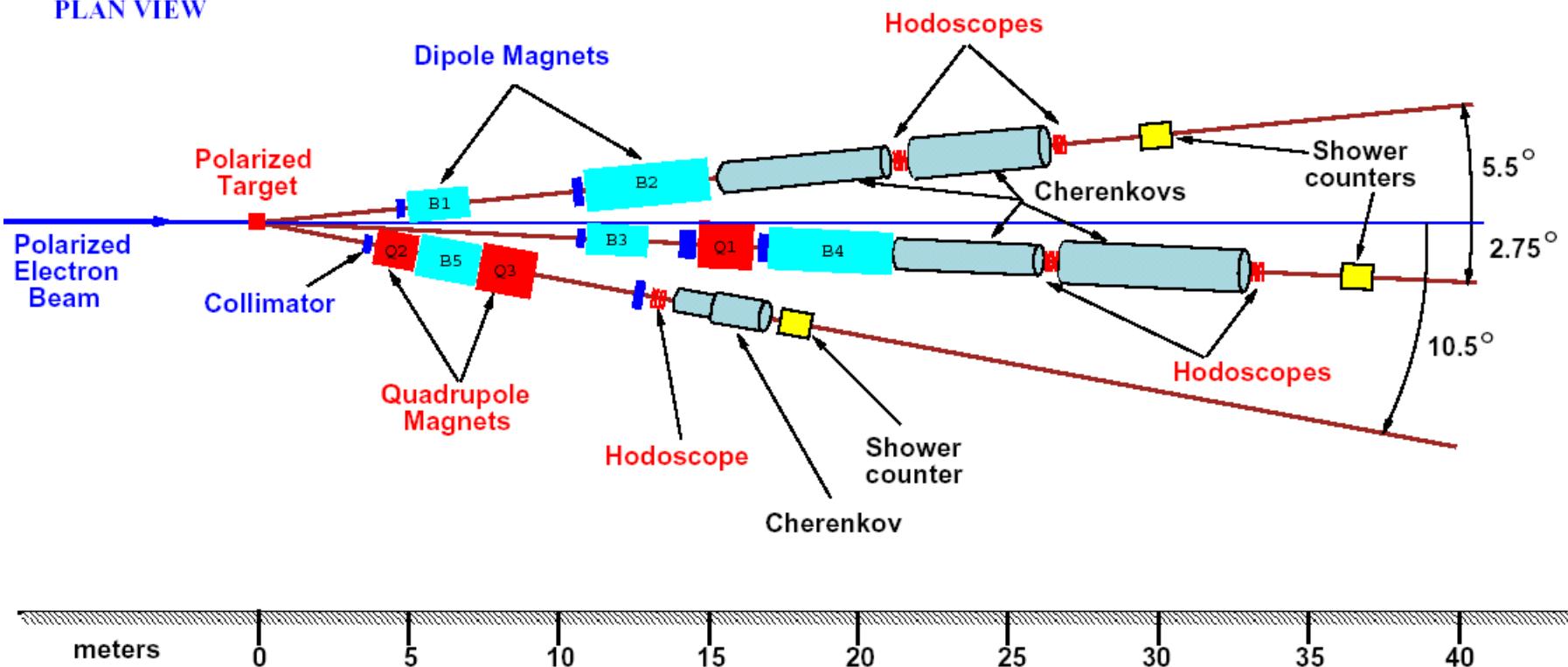


COMPARISON OF PROGRAMS

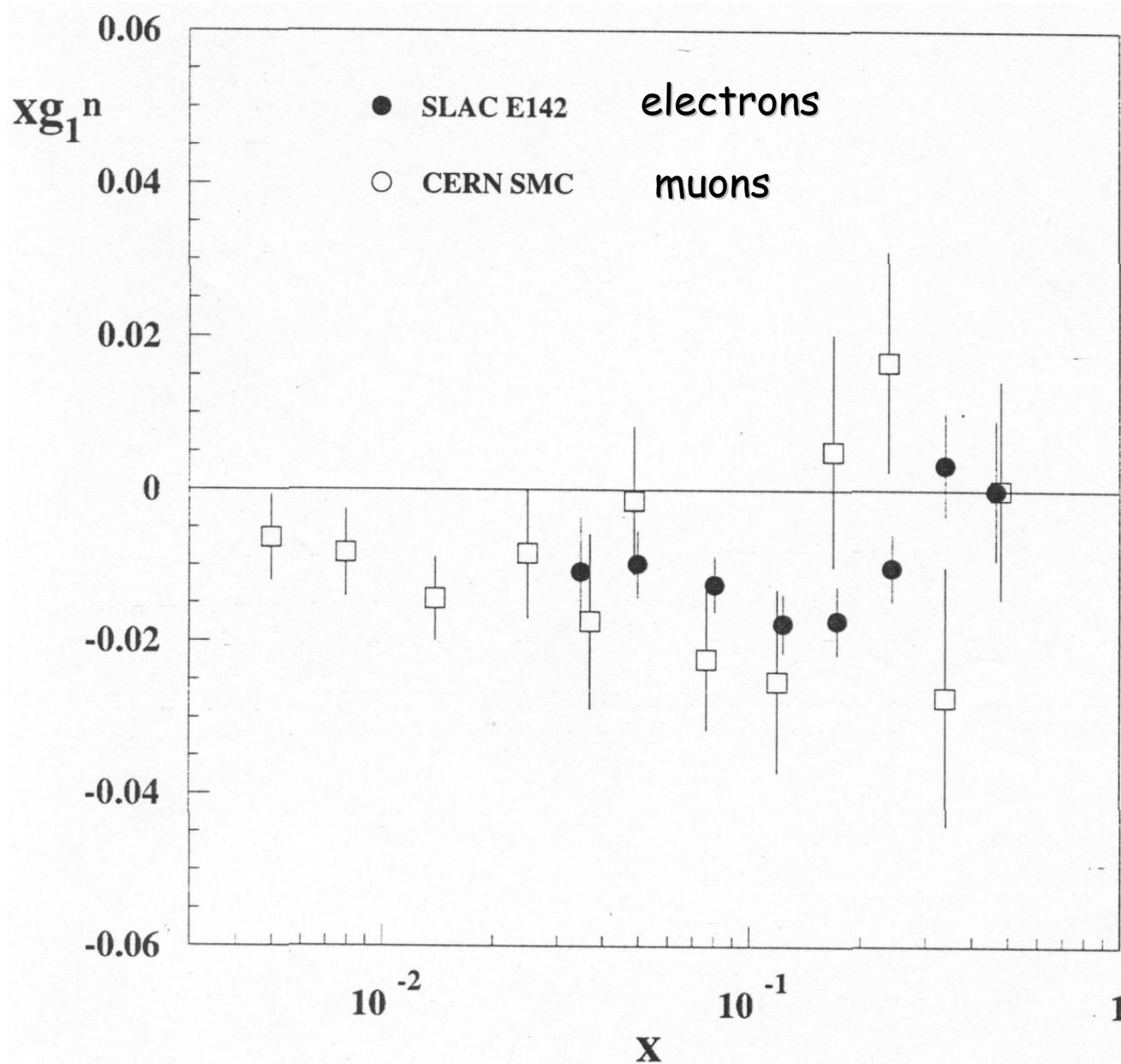
<u>Experiment</u>	<u>Beam</u>	<u>Energy</u>	<u>Target</u>	<u>Years</u>
CERN EMC	muons	200 GeV	proton	1987-1988
CERN SMC	muons	100-200 GeV	proton deuterons	1993-1998
DESY HERMES	positrons	27 GeV	proton deuteron ^3He	1995-today
SLAC E142	electrons	22 GeV	^3He	1993-1995
E143	electrons	29 GeV	proton deuteron	1994-1996
E154	electrons	50 GeV	^3He	1997
E155	electrons	50 GeV	proton deuteron	1998-2002

SLAC Polarized Deep Inelastic Scattering Experiments

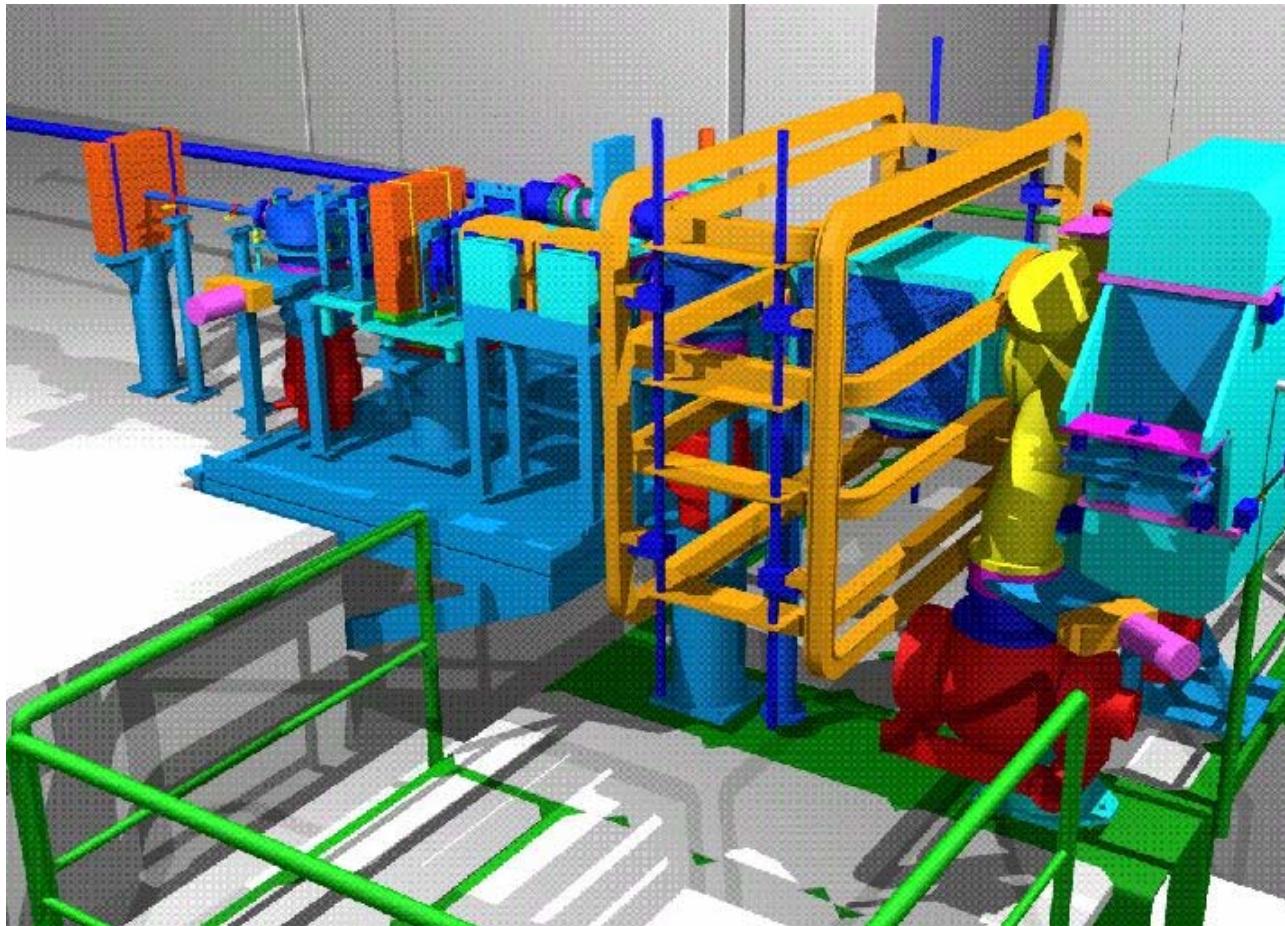
PLAN VIEW

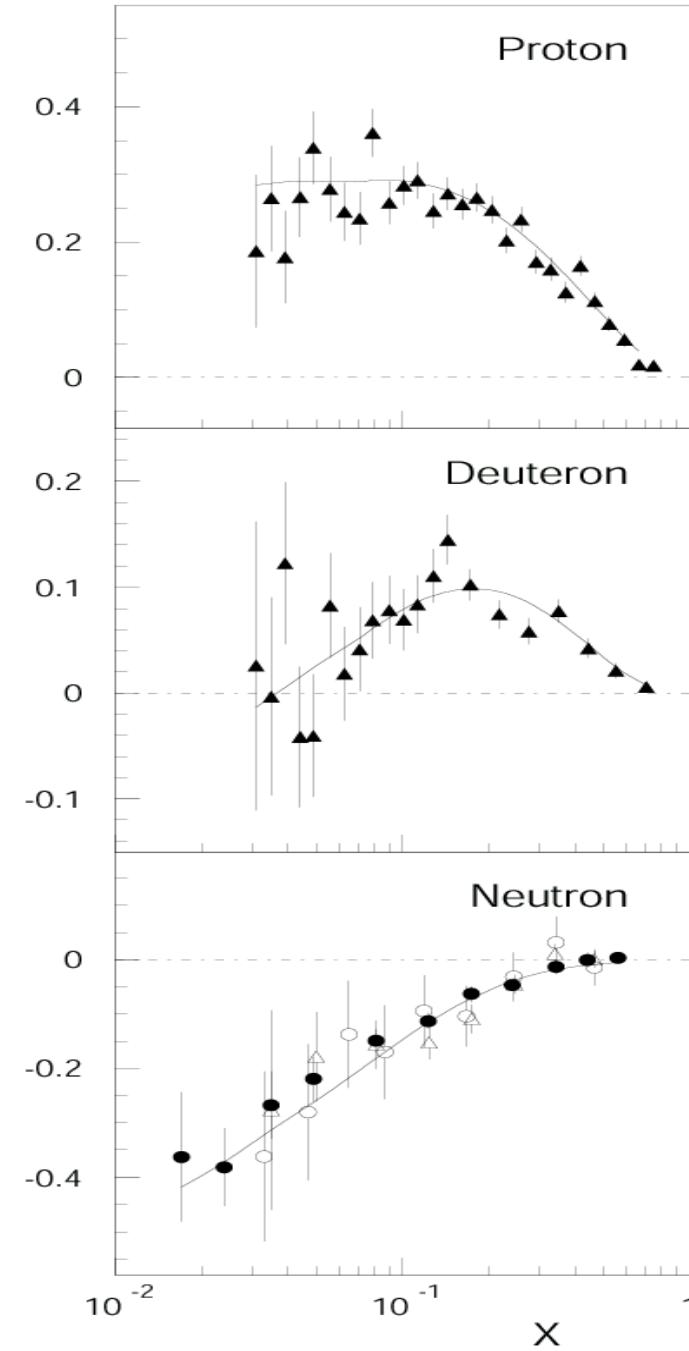
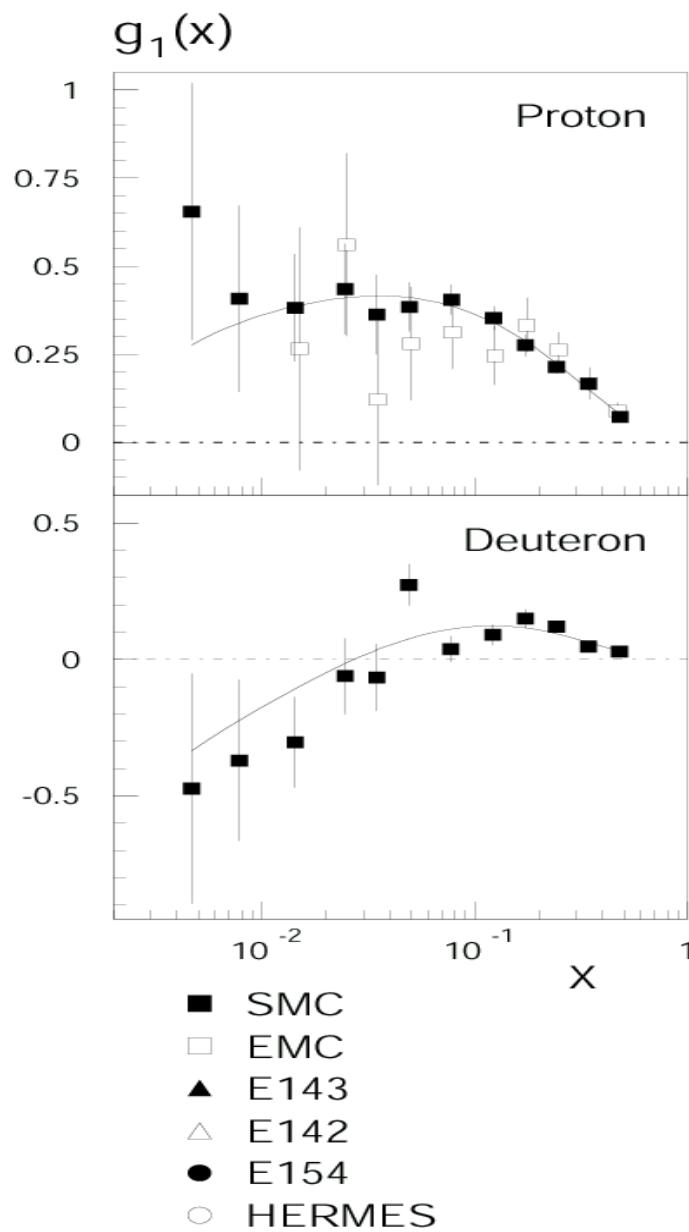


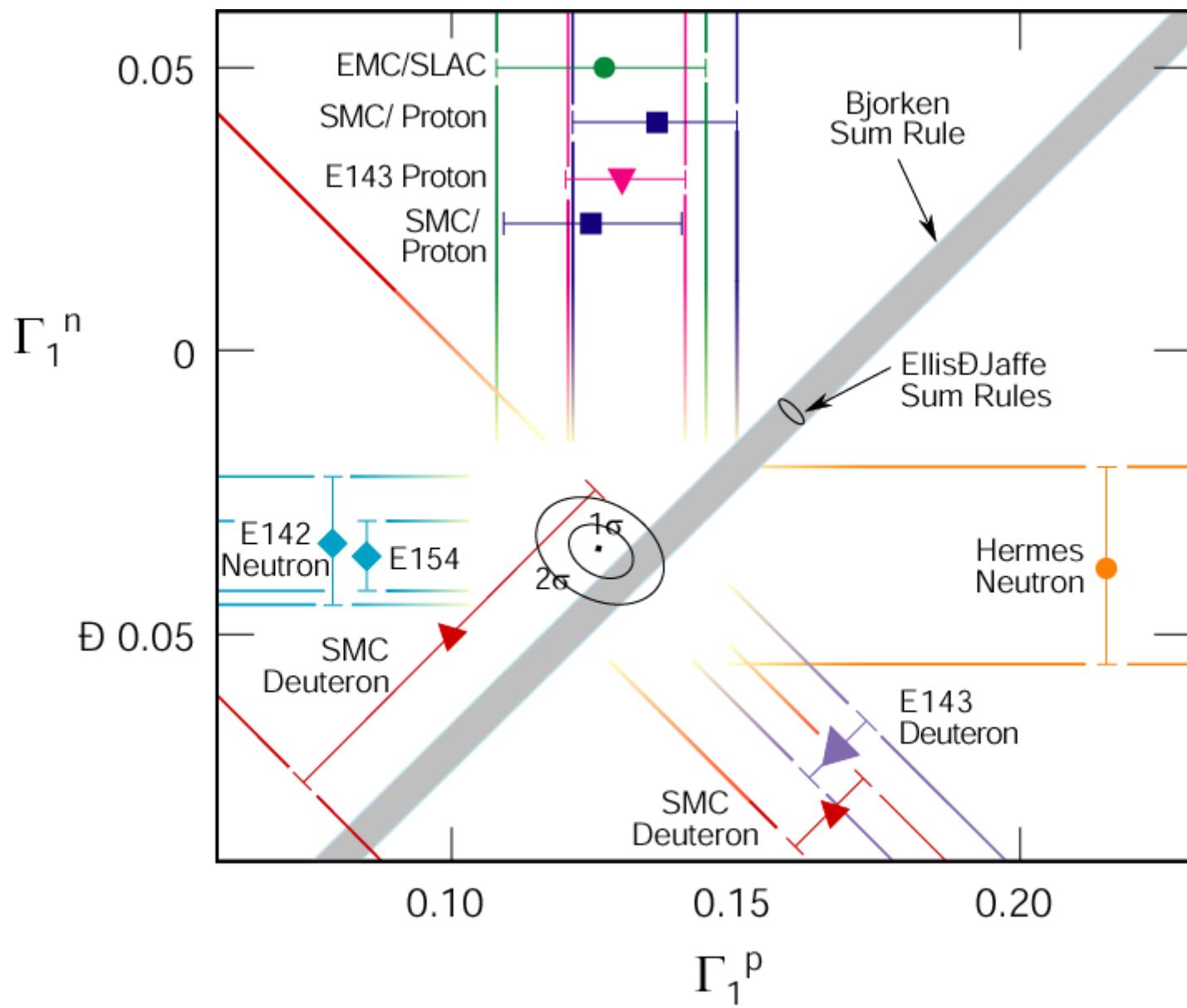
1992-1995 Neutron Measurements

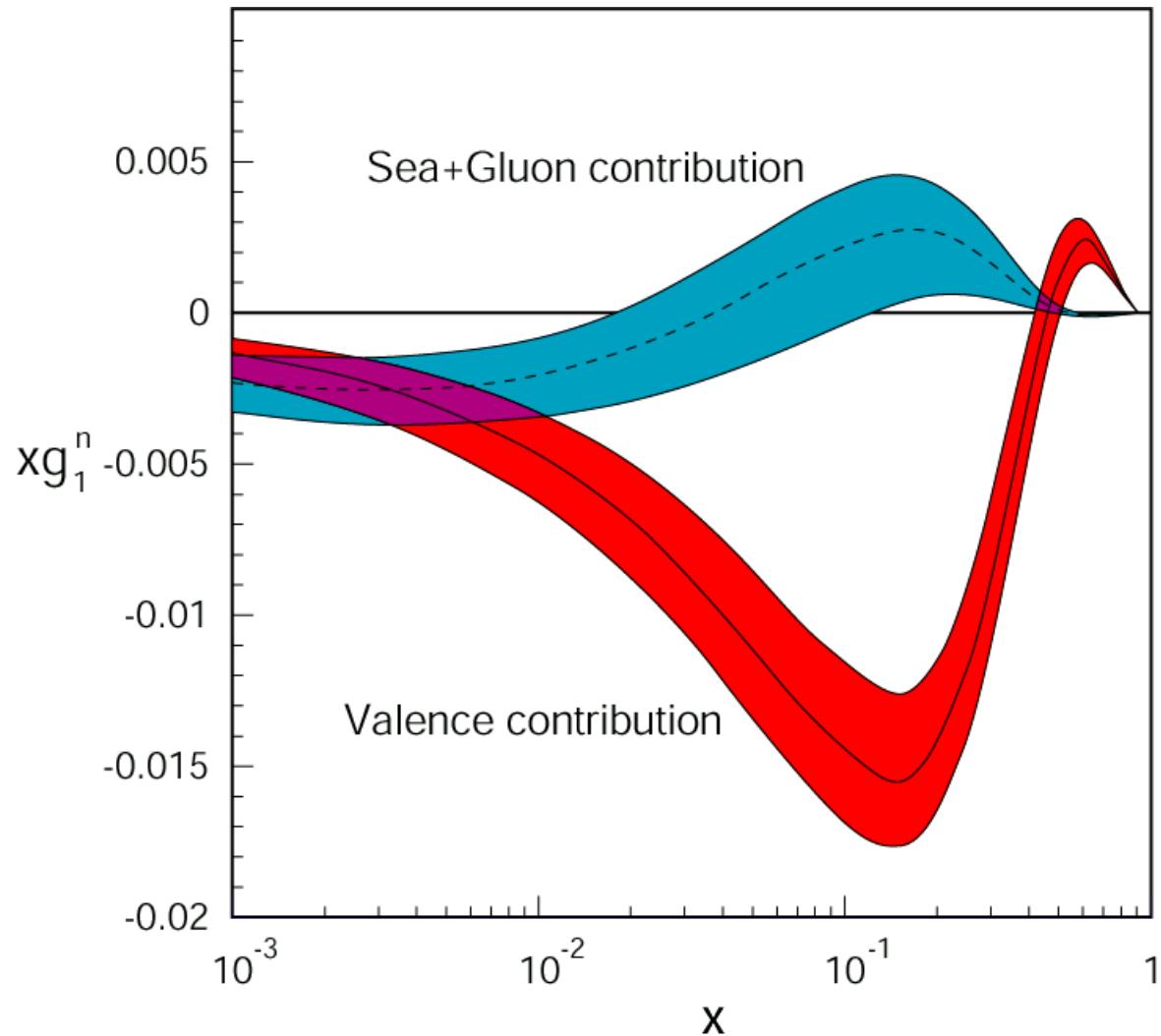


HERMES DETECTOR

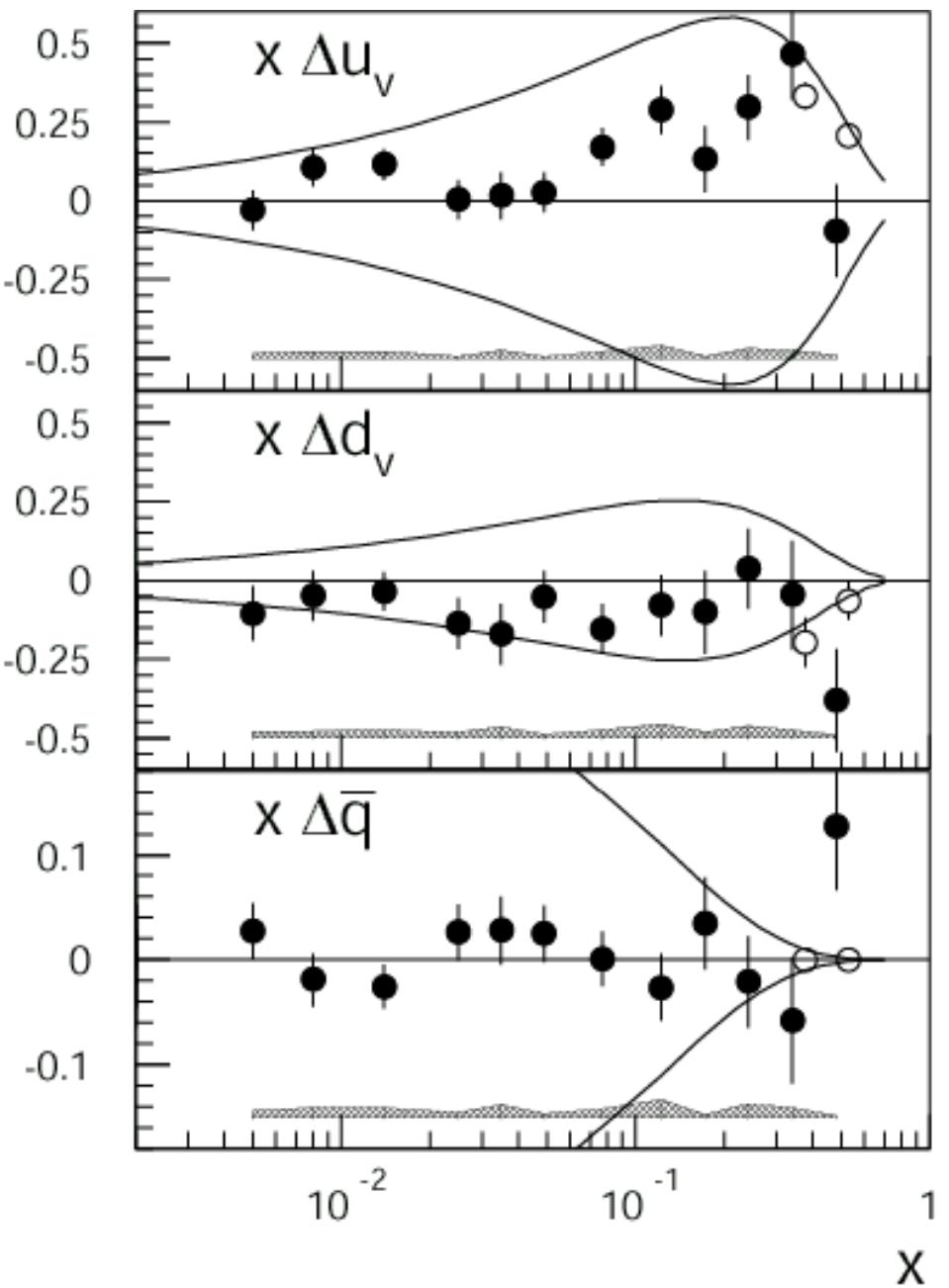


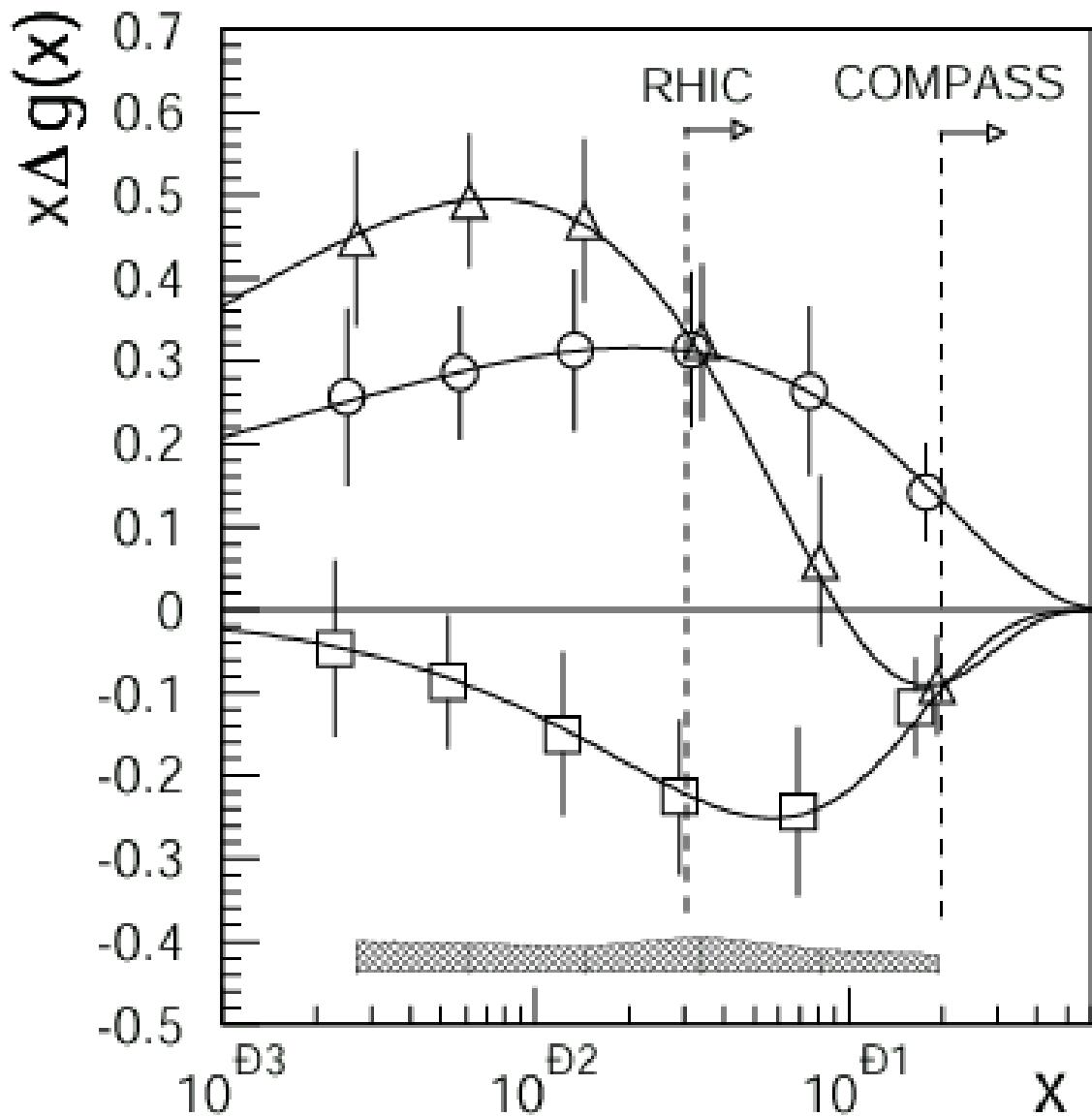






Results from SMC Semi-inclusive scattering





SUMMARY

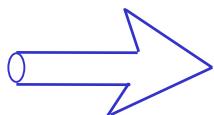
quark

$$\Delta q \approx 0.2 \pm 0.1$$

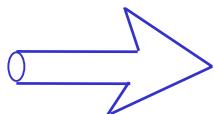
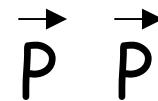
gluon

$$\Delta G \approx 1.8 \pm 1.$$

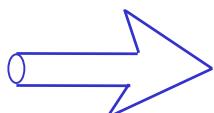
Hunting ΔG



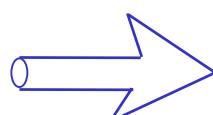
RHIC Spin



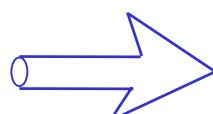
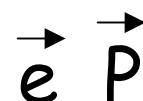
CERN COMPASS



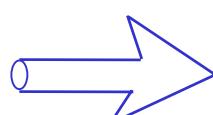
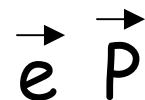
DESY HERMES



DESY Polarized HERA



Brookhaven EIC



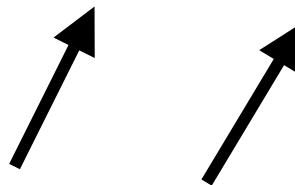
SLAC E161



* coming soon

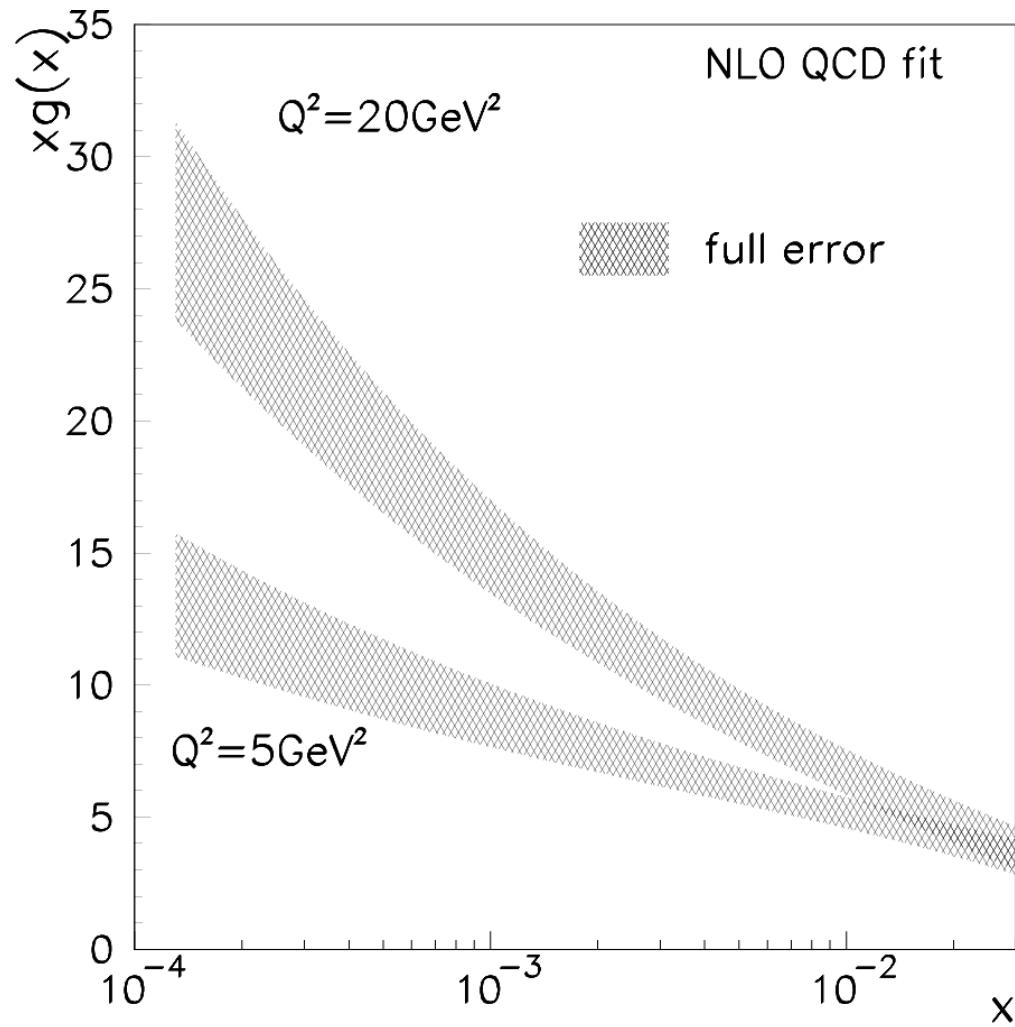
BUT.....

$$S = \frac{1}{2} = \frac{1}{2}\Delta q + \Delta G + L_q + L_G$$



orbital angular
momenta

What do we know about $G(x)$?



CENTER OF MASS ENERGY

200 GeV muons



Protons

$$\sqrt{s} = 20 \text{ GeV}$$

Bjorken-x down to 10^{-3}

30 GeV electrons



900 GeV protons



$$\sqrt{s} = 330 \text{ GeV}$$

Bjorken-x down to 10^{-4}

What about the hyperfine structure of hydrogen??

Hyperfine splitting $\longrightarrow \delta_P(\text{pol})$

$$\delta_P(\text{pol}) \sim \frac{G_1(v, q^2)}{v}$$

Small $v \longrightarrow$ resonance region

CEBAF physics!

SLAC E142 COLLABORATION

P.L. Anthony, R.G. Arnold, H.R. Band, H. Borel, P.E. Bosted, V. Breton, G.D. Cates, T.E. Chupp, F.S. Dietrich, J. Dunne, Robin D. Erbacher, J. Fellbaum, H. Fonvieille, R. Gearhart, R. Holmes, E.W. Hughes, J.R. Johnson, D. Kawall, C. Keppel, S.E. Kuhn, R.M. Lombard-Nelsen, J. Marroncle, T. Maruyama, W. Meyer, Z.E. Meziani, H. Middleton, J. Morgenstern, N.R. Newbury, G.G. Petratos, R. Pitthan, R. Prepost, Y. Roblin, S.E. Rock, S.H. Rokni, G. Shapiro, T. Smith, P.A. Souder, M. Spengos, F. Staley, L.M. Stuart, Z.M. Szalata, Y. Terrien, A.K. Thompson, J.L. White, M. Woods, J. Xu, C.C. Young, G. Zapalac

48 authors

SLAC E155 COLLABORATION

P.L. Anthony, R.G. Arnold, T. Averett, H.R. Band, M.C. Berisso, H. Borel, P.E. Bosted, S.L. Bultmann, M. Buenerd, T. Chupp, S. Churchwell, G.R. Court, D. Crabb, D. Day, P. Decowski, P. DePietro, Robin D. Erbacher, R. Erickson, A. Feltham, H. Fonvieille, E. Frlez, R. Gearhart, V. Ghazikhanian, J. Gomez, K.A. Griffioen, C. Harris, M.A. Houlden, E.W. Hughes, C.E. Hyde-Wright, G. Igo, S. Incerti, J. Jensen, J.R. Johnson, P.M. King, Yu.G. Kolomensky, S.E. Kuhn, R. Lindgren, R.M. Lombard-Nelsen, J. Marroncle, J. McCarthy, P. McKee, W. Meyer, G.S. Mitchell, J. Mitchell, M. Olson, S. Penttila, G.A. Peterson, G.G. Petratos, R. Pitthan, D. Pocanic, R. Prepost, C. Prescott, L.M. Qin, B.A. Raue, D. Reyna, L.S. Rochester, S. Rock, O. Rondon-Aramayo, F. Sabatie, I. Sick, T. Smith, L. Sorrell, F. Staley, S. St. Lorant, L.M. Stuart, Z. Szalata, Y. Terrien, A. Tobias, L. Todor, T. Toole, S. Trentalange, D. Walz, R.C. Welsh, F.R. Wesselmann, T.R. Wright, C.C. Young, M. Zeier, H. Zhu, B. Zihlmann

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CERN SMCC COLLABORATION

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